

**THE RELATION BETWEEN THE
MAGNITUDE OF STIMULUS
AND THE TIME OF
REACTION**

BY

SVEN FROEBERG, PH.D.

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EDITED BY R. S. WOODWORTH

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I. INTRODUCTION

Of the methods employed in experimental psychology, scarcely any has been more useful and more extensively applied than the method of reaction time. The extensive literature on the subject shows that it has been employed in the study of the most diverse mental processes, and is at present successfully applied to such problems as the measurement of differences in sensations, individual differences, the transference of function, the psychology of the insane, etc., and that valuable data bearing on such problems are rapidly accumulating. In order that these may be made reliable and directly comparable, other factors, not related to the problem, must be excluded or their influence taken into consideration. One of these factors, the influence of which is always present but seldom considered, is the influence of the magnitude of the stimulus. The results will differ according as the stimulus is strong or weak, and such differences may be large enough to obscure the factors which it is desired to investigate. From a purely technical point of view it becomes desirable, therefore, to determine the influence of variation in the magnitude of the stimulus on the time of reaction. But besides this the problem has also an intrinsic interest. The relation between the stimulus and sensation has received an extraordinary amount of attention in the past, and a knowledge of the relation between stimulus and movement or action may turn out no less interesting and valuable.

Some attention has already been devoted to the problem, but it has been confined to only one aspect of it, and the results obtained have been discordant and unsatisfactory. The need of a careful repetition of the older experiments on the influence of the intensity of the stimulus and a determination of the hitherto unknown influence of size and duration on the time of reaction may therefore be regarded as sufficient justification of this new attempt at an old problem.

The work here reported on has been concerned chiefly with visual stimuli, since these are more easily measured and naturally offer the best field for experiments on all the factors involved. For purposes of comparison, experiments have also been made on different intensities of sound. In order to obtain equal experimental conditions and thus render the results directly comparable, the experiments on the several factors have not been separated but made in the same series. For the sake of clearness and convenience, however, each factor will be treated separately, after which a comparison of the stimulus values of each will be made.

II. APPARATUS AND METHOD

The visual stimuli consisted of ordinary daylight reflected from paper of varying degrees of brightness. These have certain advantages over transmitted light in that they conform more to natural conditions and are more easily handled, but have also the disadvantage that they vary with varying daylight. It was not an easy matter to obtain an apparatus which would fulfil all the conditions of the experiment, *viz.*, allow the size, intensity and duration of the stimulus to be varied and at the same time give a noiseless and approximately instantaneous exposure. The apparatus which was finally used met these requirements fairly well, though it did not allow as wide a variation of intensity and time of exposure as would have been desirable. It consisted of an iron wheel, 92 cm. in diameter, with a rim 17 cm. wide, mounted on a table, with its axis in a vertical position and driven by an electric motor. The speed of the wheel was regulated by a resistance coil and kept uniform at the rate of one revolution in three seconds. The paper furnishing the stimulus was mounted on a projection on the rim of the wheel. This increased its diameter so that the rate at which the paper traveled was 1 mm. per σ , and also served to darken the background by removing the rim of the wheel to some distance from the source of light. Thus, except in the case of the two largest sizes, the background presented an absolute black. On the table between the wheel and the observer a screen was fixed, in the middle of which was an aperture 16 x 16 cm. Into this, smaller paper screens with apertures varying in size from 3 to 48 mm. sq. were inserted. As the wheel moved, the paper furnishing the stimulus moved past this aperture. Ordinarily, it was covered by a movable metal screen, controlled by the operator by means of a string running on pulleys. About $1\frac{1}{2}$ seconds before the stimulus was exposed, the screen was raised and the subject's attention fixed on the black aperture. The subject was seated in front of the screen with his hands on the table and the fingers of his right hand on a telegraph key. To measure the reaction-time an ordinary Hipp chronoscope was used. This, together with resistance coils, switch keys, etc., were placed on an adjoining table at which the recorder worked. The latter was shut off from the subject's view by another screen. This isolation of the subject was found necessary since the movements of the recorder would otherwise disturb him and tend to produce premature reactions. The noiseless closing of the contact simultaneously with the exposure of the stimulus was effected by a device first suggested by Professor Cattell. It consisted of a circular rim, half of which was of brass and half of a non-conducting substance, fastened to the upper side of the wheel. On this rim rested another strip of brass with sufficiently great pressure

to make a good contact without causing an unnecessary amount of friction. Both the rim and the brass strip were connected by wires with the main circuit. Thus the circuit was open when the brass strip passed over the non-conducting material, and closed when it passed over the brass. The course of the current was as follows: From the battery to the switch key, then to the sliding contact, through the telegraph key, then through the resistance coil, through the chronoscope, and back to the battery. In the pendulum tachistoscope first used the noise produced by the closing of the contact disturbed the subject, and often caused him to react to the sound instead of to the visual stimulus, even when the sound came 100 σ later. The tachistoscope described by Wundt¹ has a mercury contact, which may reduce the noise considerably without being entirely noiseless when the subject is close by. The motor and the wheel made a slight uniform noise, which, however, did not seem to disturb the subject in the least. On the contrary, it served to drown the small click produced in the chronoscope when the stimulus was exposed and the circuit closed. It may be that failure to take account of and exclude this cause of disturbance has been the source of considerable errors in some of the published experiments on reaction-time. The current for the chronoscope was supplied by 6 gravity cells and varied little from day to day. Nevertheless, to insure accuracy in the results, the chronoscope was tested before and after each series by means of a Cattell fall-chronometer. The apparatus was placed in front of an eastern window in a large room on the third floor of the building in such a manner that it received the full light from the sky but not the direct rays of the sun. The experiments were made between the hours of ten and four. On very dark days no experiments were made. The light conditions did vary somewhat from day to day, but this affects only the absolute and not the relative value of the results. Care was also taken to have the physical and mental condition of the subjects good. The number of experiments made at each sitting was 200 to 225, except in the case of sound, where it was 400. Reactions to sound seemed less fatiguing than reactions to visual stimuli, and 400 seemed not too great a number for a single sitting. The series on visual stimuli usually took about 50 minutes, and those on sound about 70 minutes. From 4 to 8 pauses were made in each series during which the subject had a few minutes' rest while the recorder changed the stimulus. Five persons have acted as subjects, H., F., R., W. and B., all of whom were either officers or students in the department of psychology and, with the exception of R., had had considerable practise in reaction-time experiments before acting as subjects in the experiments of the present investigation.

¹ *Physiol. Psychol.*, 4 ed., Bd. II., p. 334.

III. THE EFFECT OF VARIATION OF INTENSITY ON THE TIME OF REACTION

Investigations into the relation between the magnitude of the stimulus and the time of reaction have almost exclusively been concerned with this factor. Von Kries and Auerbach,¹ though not directly interested in the subject, discovered that the time of reaction decreased as the intensity of the stimulus increased. Similarly Exner,² in a series of reactions to an electric spark, found that as the length and consequently also the brilliancy of the spark increased, the time of reaction was reduced from 158σ to 123σ . Wundt³ in reaction experiments on sound found that, as he increased the intensity of the sound by increasing the height of fall of the sound hammer from 1 mm. to 16 mm., the time of reaction decreased from 217σ to 125σ , and by increasing the height of fall of a ball from 2 to 25 cm., the time of reaction decreased from 176σ to 159σ . Thus, on the whole, an inverse relation was found to exist between the intensity of the stimulus and the time of reaction, but the decrease was not sufficiently regular to show a more definite relation. No attempt was made by von Kries and Auerbach nor by Exner to explain their results. Wundt, however, explained them as due to the relation of the stimulus to attention. Reactions are faster to those stimuli which lie within the range of normal attention, but slower to those to which the attention has to be accommodated. On this theory, intensities above the normal should give slower reactions similar to those below it, a hypothesis which, however, subsequent experiments have not confirmed.

The most extensive study of the problem so far has been made by Berger⁴ and Cattell⁵ in the Leipzig laboratory. Their experiments extended over three sense departments, the visual, the auditory and the tactile (electric stimulation). For visual stimuli light produced by sending an electric current through a Puluj tube was used, and the various intensities were obtained by means of smoked glasses. These, calling the full intensity of the light 1000, were 1, 7, 23, 123, 315, and 1000. Two greater intensities which were not measured were also used. A summary of the results on two subjects is given below:

¹ *Arch. f. Anat. u. Physiol.*, 1877, p. 357.

² *Pflüg. Arch.*, 7, 625.

³ *Physiol. Psych.*, 2 Ed., Bd. II., p. 224

⁴ *Philos. Stud.*, 3, 38, 1886.

⁵ *Brain*, 32, 1886.

Inten- sity.	I.	II.	III.	IV.	V.	VI.	VII.	VIII.
Av.	338	265	238	230	222	225	207	198
B.								
M.V.	26	18	16	15	15	17	18	16
Av.	281	205	190	178	177	173	165	158
C.								
M.V.	30	17	16	14	15	13	16	19

The results from experiments on sound and electric stimuli where, however, only four intensities were used, were similar to those above and need therefore not be given. On the basis of these results the investigators concluded that the time of reaction decreases with increasing intensity of the stimulus, faster near the threshold, but more slowly as the region of normal intensities is approached. Apparently, they had expected to find a more definite relation between the variation in intensity and the time of reaction, for the logarithms of the different intensities are calculated and curves are constructed in which the distances on the axis of abscissas are proportional to the logarithms of the stimulus and the ordinates proportional to the times of reaction. But, as the results show, neither the logarithmic nor any other relation appears to hold.

Cattell and Dolley¹ also made some experiments to determine the influence of the intensity of the stimulus on the time of reaction. They found that for electric stimulation, touch and blows, the time of reaction decreased with increasing intensity of the stimulus. Only three intensities were used, however, and these were not measured, with the exception of the blows. The results from experiments on the latter are given in the table below. The intensity is expressed in terms of the height of fall of the hammer producing the stimulus.

Int.	J.		C.		D.	
	Av.	M.V.	Av.	M.V.	Av.	M.V.
15	118.7	10.9	118.4	6.6	148.9	11.3
30	114.0	9.6	118.6	7.6	146.9	11.3
60	111.4	9.2	116.2	6.5	148.4	11.5

Concerning these results, Cattell says: "The reaction-time thus becomes shorter as the intensity of the stimulus is increased, but the difference in time is small so long as the stimuli are moderately strong. The difference is, indeed, so small that it is obscured by the error of observation, but in the final average of the three thousand four hundred reactions the time was decreased 1.3σ when the intensity was increased from 15 to 30 grams, and decreased 1.7σ when the intensity was increased from 30 to 60 grams. If, as Fechner's law assumes,

¹ "On Reaction-time and the Velocity of the Nervous Impulse." *Nat. Acad. of Sci.*, 1893, 7, 393.

the intensity of the sensation increases as the logarithm of the stimulus, the reaction-time tends to decrease inversely as the intensity of the sensation."

In the last two investigations reported, every care seems to have been taken to eliminate all disturbing factors. Nevertheless, the lack of agreement between the several subjects and the irregularity with which the time of reaction decreases point to the presence of errors, which so far have escaped detection, but have been large enough to obscure any relation that may exist. It has been the custom to measure the reliability of an average by the size of the so-called probable error as expressed by the formula,

$$P.E. = M.V. \times .84435/\sqrt{n},$$

where M.V. is the mean variation and n is the number of measurements. This implies, however, the assumption that the variations are due wholly to chance and fall equally above and below the average. That psychophysical processes are subject to chance variation there is little doubt. But besides this sort of variation there seems to be another which gives rise to semi-constant errors, *i. e.*, errors which are constant for a longer or shorter period and then either disappear or are reversed. The causes of these errors are difficult to discover. They may possibly be due to an unconscious change in the state of attention, or they may be due to periodic changes in the subject, either physical or mental, or both. It would be interesting to investigate further the causes and operation of these semi-constant errors, but such an undertaking is outside of the limits of this research. The presence and influence of such errors can be detected in almost all work on psychophysics and psychometry. The results have seldom corresponded to what they theoretically should be, even when chance errors are allowed for; but the discrepancy, when not too large, has usually been neglected. In experiments on reaction-time, however, where small differences would be significant, these errors are liable to obscure the results, so that only the most general conclusions can be drawn. Especially is this the case where the number of experiments is small and the subject unpractised. It was found early in the course of the present experiments that the smaller the number of reactions the more the results would suffer from these errors. This led to an increase in the number of reactions from 225, as was first intended, to 400 to each stimulus. It is probable that more experiments would increase still further the uniformity and reliability of the results. Returning now to the earlier experiments, it is evident that they can have little if any value, obtained as they were from only 15 to 20 reactions. Even the results of Berger and Cattell, though obtained from an average of 150

reactions, must be subject to this error to a considerable extent. If the cause cannot be eliminated, and so far no way of doing so has been found, the only course open is to make the experiments sufficiently numerous for these semi-constant errors to be distributed equally throughout every part of the series and thus reduce them to chance errors. Though this may not be completely accomplished in the present case, it is nevertheless believed that an approximation to it has been made by the greater number of reactions and by the discontinuation and rejection of all series in which abrupt and marked changes in the reaction-time occurred.

There is also another source of error, not hitherto taken account of, which in some subjects may impair and even invalidate the results. It is well known that the so-called "warming up" tends to decrease the time of reaction, and that fatigue tends to increase it. To eliminate these influences it has been customary to make the second half of the experiment in the inverse order. But this will eliminate them only in case they operate uniformly throughout the series. From repeated observations, however, this seemed not to be the case, as also the accompanying figures, chosen at random from a number of similar results, show. The first is the average of the first 25 reactions of nine series, the second of the next 25, etc. The stimuli are the same in each case. All the objective, and as far as possible also the subjective, conditions then being equal, the averages should be the same throughout.

168.0 169.0 168.3 162.1 165.8 169.5 169.5 168.9 171.0

It appears that there is a place in the middle of each series where the "warming up" effect has ceased and the fatigue effect has not yet begun to assert itself. The difficulty will not be removed by making the second half of the experiment in the inverse order. The only way to eliminate this source of error is to distribute the several stimuli equally throughout the series. This was accomplished by beginning each series with a new stimulus and making the first in one series the last in the next, next to the last in the third, etc. These precautions being taken against errors, it is believed that the results obtained are fairly reliable.

The aim was to vary all the three factors of the magnitude in the same series and thus be able to compare them directly with one another. But as this could not be done on account of the mechanical limitations of the apparatus, it was found necessary to divide the experiments into two parts, in the first of which the intensity and the size were varied and in the second the intensity and duration.

The greatest intensity, denoted by 100, was that of the Milton-Bradley white baryta paper. The other intensities were obtained from Hering's grays and their brightness in comparison with the

TABLE II

Subject W

2000 reactions

Ser.	100		56		25		16		10	
	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.
I.	155.3	14.0	174.2	10.0	172.2	9.4	161.0	9.1	164.0	10.6
II.	155.5	5.3	164.8	10.7	178.1	16.0	182.7	10.2	176.4	8.8
III.	162.4	8.8	166.4	8.3	161.1	6.0	170.8	8.5	164.5	6.2
IV.	160.6	6.1	164.1	10.3	161.8	8.5	169.1	11.8	174.0	13.6
V.	163.5	8.2	167.5	6.3	173.9	7.0	172.6	8.7	188.0	12.0
VI.	162.3	5.7	167.0	10.7	167.2	9.2	174.2	9.3	174.1	11.6
VII.	164.2	11.9	175.2	9.3	186.0	12.0	189.0	9.8	183.6	7.2
VIII.	158.6	9.1	153.2	6.0	156.6	6.5	176.2	9.4	176.4	8.5
IX.	164.0	9.2	175.8	10.1	179.5	9.0	181.0	11.1	197.1	11.0
X.	175.8	9.8	174.4	8.0	179.1	10.1	179.4	12.3	190.2	11.4
XI.	177.3	6.5	179.2	11.1	184.2	7.0	185.2	6.8	193.4	8.1
XII.	178.3	10.2	176.2	9.0	178.2	7.3	188.1	11.0	183.7	8.8
XIII.	177.8	12.1	187.3	7.1	188.5	10.9	188.1	11.9	184.9	13.2
XIV.	197.7	11.0	204.3	11.4	210.4	12.1	196.0	13.4	203.1	13.8
XV.	194.8	12.5	188.6	11.2	188.4	8.8	188.3	8.9	182.7	7.5
XVI.	205.0	11.4	205.8	12.3	200.2	9.8	203.6	10.7	212.8	13.9
Av.	172.1	9.5	176.0	9.5	179.1	9.4	181.6	10.2	184.2	10.4
P.E.	.40		.40		.40		.43		.44	

TABLE III

Subject R

2000 reactions

Ser.	100		56		25		16		10	
	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.
I.	185.5	10.3	188.8	8.7	191.5	9.7	199.0	10.1	199.2	9.0
II.	190.1	11.4	185.6	9.6	189.4	7.6	197.8	9.0	210.3	17.6
III.	194.6	12.0	188.5	12.2	199.2	10.5	206.3	16.9	223.3	10.2
IV.	187.8	10.3	184.9	9.1	198.6	12.5	196.6	12.9	209.6	16.3
V.	187.6	12.2	188.4	11.6	198.6	12.0	214.5	11.3	211.4	10.4
VI.	179.4	12.2	190.1	9.5	188.2	15.0	197.4	13.1	200.7	8.6
VII.	181.8	12.1	174.4	12.0	177.6	10.8	184.0	13.7	190.4	17.1
VIII.	175.0	15.7	182.6	11.8	188.0	15.6	175.9	12.6	185.8	10.0
IX.	188.2	13.6	182.9	9.2	185.9	13.1	191.2	9.1	191.2	10.2
X.	204.2	8.2	201.3	11.2	215.5	9.6	218.7	10.8	219.3	9.4
XI.	197.2	10.1	200.6	7.3	203.3	8.6	210.5	9.6	213.2	10.9
XII.	206.0	13.4	211.0	13.7	199.7	8.8	202.6	16.3	217.2	12.0
XIII.	205.5	9.4	215.4	7.2	206.7	11.2	208.9	8.2	213.7	14.0
XIV.	196.9	8.2	209.2	9.7	210.1	8.4	215.1	7.6	224.2	12.4
XV.	192.1	10.4	205.9	8.2	202.2	8.9	206.4	8.6	212.8	10.5
XVI.	199.2	11.2	197.6	6.7	198.6	8.3	198.1	10.0	206.1	9.8
Av.	191.1	11.3	194.2	9.9	197.1	10.7	201.5	11.2	208.0	11.8
P.E.	.48		.42		.45		.47		.50	

TABLE IV
Subject W 2000 reactions

Ser.	100		56		25		16		10	
	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.
I.	165.3	7.6	166.4	7.0	168.1	5.9	181.1	9.1	180.2	8.7
II.	168.3	7.0	168.5	6.5	173.0	8.2	173.6	8.4	172.1	8.3
III.	170.6	6.7	171.6	5.0	182.1	8.0	176.2	6.8	176.4	6.4
IV.	182.7	9.8	183.0	8.0	188.0	6.3	192.2	7.4	192.2	9.5
V.	176.9	4.6	183.4	6.9	184.4	8.7	186.2	8.7	188.3	5.7
VI.	171.0	6.5	176.4	6.5	173.8	7.8	173.8	7.5	176.9	6.4
VII.	158.8	7.4	165.9	6.4	171.5	4.7	178.8	9.0	179.7	6.0
VIII.	154.2	11.4	158.9	7.0	172.2	12.5	173.7	10.8	169.8	7.6
IX.	164.4	9.7	163.5	9.3	164.6	6.3	167.8	9.6	175.4	7.2
X.	173.5	8.7	181.7	8.0	196.0	9.8	186.0	10.4	187.0	5.7
XI.	173.6	5.3	173.6	7.8	183.8	9.5	182.8	9.4	180.2	7.1
XII.	181.2	9.2	176.0	7.3	180.3	7.1	186.8	7.8	198.6	14.8
XIII.	181.2	6.4	174.2	12.0	186.2	7.1	199.6	11.2	195.2	9.0
XIV.	180.4	8.4	185.8	6.2	192.9	11.0	204.2	16.8	203.6	9.0
XV.	181.4	8.1	187.9	11.4	178.2	7.3	180.4	9.2	186.1	9.3
XVI.	190.1	10.0	197.0	8.4	192.9	8.4	191.8	8.8	198.8	12.3
Av.	173.4	7.9	175.9	7.7	180.5	8.0	183.4	9.4	185.0	8.3
P.E.	.33		.32		.34		.40		.35	

Each figure in the body of the tables gives the average of 25 reactions; the final averages thus include 400 cases each. In Tables I. and II. the size of the stimulus is 48 mm. sq., corresponding to the largest stimulus in the series on sizes. In Tables III. and IV. the size is 3 mm. sq., corresponding to the size in the time series.

When these experiments were nearly completed it was suggested that the intensities be decreased until the threshold was reached. Four more intensities are therefore added, namely $6\frac{3}{8}$, $3\frac{1}{8}$, $2\frac{1}{4}$, and $\frac{3}{4}$. These were determined in the same manner as before. The measurements are given in detail in the accompanying table:

F.	$6\frac{3}{8}$	$3\frac{1}{8}$	$2\frac{1}{4}$	$\frac{3}{4}$
R.	$6\frac{3}{8}$	$3\frac{1}{8}$	$2\frac{1}{4}$	$\frac{25}{32}$
W.	$6\frac{1}{2}$	$3\frac{1}{8}$	$2\frac{1}{4}$	$\frac{20}{32}$
Av.	$6\frac{3}{8}$	$3\frac{1}{8}$	$2\frac{1}{4}$	$\frac{3}{4}$ appr.

The lowest intensity was a velvet-black and nothing blacker than this could be obtained. It was still a considerable distance above the threshold. By decreasing the time of exposure, which theoretically decreases the intensity proportionally, the threshold was reached when this stimulus was exposed for about 5σ , about $\frac{1}{8}$ of the lowest intensity used. For the purpose of comparison, intensity 10 of the previous set of experiments was also included. On account

of limited time, only 200 reactions were taken to each stimulus. The results are given in Tables V. and VI. The reaction-time to intensity 10 is not the same as in Tables III. and IV., but by multiplying the averages by 208.0/206.5 and 185.0/199.5, respectively, the results are made directly comparable.

TABLE V
Subject R 1000 reactions

Ser.	10		$6\frac{2}{3}$		$3\frac{1}{3}$		$2\frac{1}{6}$		$\frac{3}{4}$	
	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.
I.	196.3	10.3	206.1	8.3	215.2	8.7	223.8	9.8	229.8	11.7
II.	219.3	7.6	207.3	8.0	229.7	9.7	231.8	11.7	244.7	9.1
III.	214.2	8.1	224.2	9.8	214.1	7.5	220.3	10.7	225.8	7.7
IV.	194.3	9.5	196.2	9.4	202.0	9.1	208.2	7.3	211.7	9.6
V.	208.4	8.5	215.8	10.0	213.8	9.5	214.9	8.0	216.5	12.3
Av.	206.5	8.8	209.9	9.1	215.0	8.9	219.8	9.5	225.7	10.1
P.E.	.53		.55		.54		.57		.61	

TABLE VI
Subject W 1000 reactions

Ser.	10		$6\frac{2}{3}$		$3\frac{1}{3}$		$2\frac{1}{6}$		$\frac{3}{4}$	
	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.
I.	189.3	11.5	192.3	7.5	192.7	8.4	200.9	9.9	201.2	7.8
II.	191.9	11.4	195.4	10.5	206.5	10.6	196.4	11.2	204.4	12.3
III.	203.1	13.3	203.0	10.9	196.0	12.2	205.8	9.9	216.3	9.2
IV.	201.0	10.3	203.8	7.7	211.5	10.4	210.6	11.3	213.0	8.8
V.	194.6	8.4	200.7	10.5	204.2	10.6	207.0	10.3	200.7	7.8
Av.	196.0	11.0	199.0	9.4	202.2	10.4	204.1	10.5	207.2	9.2
P.E.	.66		.56		.62		.63		.55	

On examining the results so far obtained we find that the time of reaction increases as the intensity of the stimulus decreases. The increase shows some irregularities which, to the writer at least, indicate that all the disturbing factors have not been eliminated. But allowing for these, the conclusion may safely be drawn that the time of reaction tends to increase arithmetically as the intensity of the stimulus decreases geometrically. To facilitate inspection, the increments in the time of reaction produced by the geometrical decrease of the stimulus are given in Tables VII. and VIII. The relation is shown graphically in Figures I. and II., where the abscissas are pro-

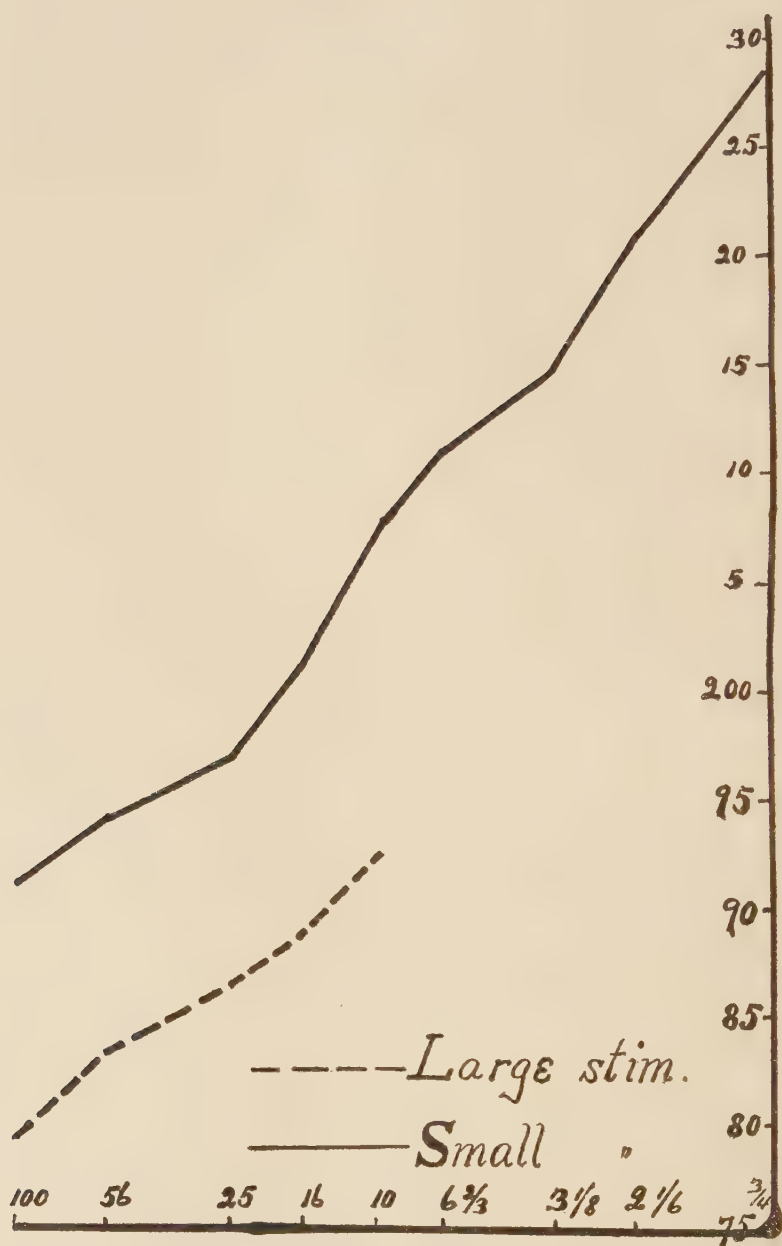


Fig. I.—Increase of the reaction-time with decrease in the intensity of the stimulus. Subject R.

portional to the logarithm of the stimulus and the ordinates are the reaction times in terms of σ .

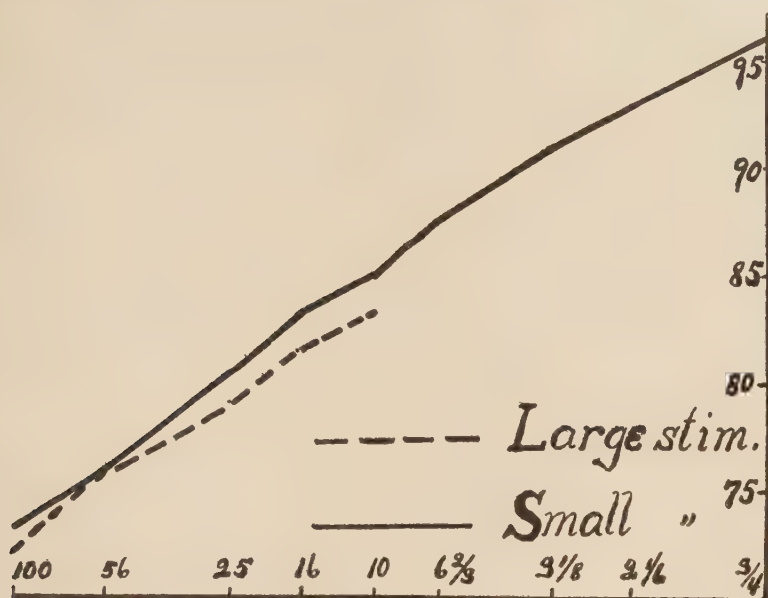


Fig. II.—Increase of the reaction-time with decrease in the intensity of the stimulus. Subject W.

TABLE VII

Int.	100	56	25	16	10
R.	Incr.	4.2	3.0	2.4	3.0
	P.E.	.44	.42	.41	.41
W.	Incr.	3.9	3.1	2.5	2.6
	P.E.	.40	.40	.42	.44

TABLE VIII

Int.	100	56	25	16	10	6 ² / ₈	3 ¹ / ₈	2 ¹ / ₆	3/4
R.	Incr.	3.1	2.9	4.4	6.5	3.4	5.1	4.8	5.9
	P.E.	.45	.44	.46	.49	.54	.55	.56	.59
W.	Incr.	2.5	4.6	2.9	1.6	3.1	5.6	1.2	3.0
	P.E.	.33	.33	.37	.38	.96	.87	.94	.96

IV. THE EFFECT OF VARIATION OF SIZE ON THE TIME OF REACTION

Scarcely any attempts have been made to determine the influence of the size of the stimulus on the time of reaction. In most cases it has been disregarded, sometimes to such an extent that the trouble is not even taken to state what sizes were used or if the size remained constant throughout the experiment.

The only reference to this subject in the literature on reaction-time is found in a study by Cattell and Dolley on reaction-time and the nervous impulse.¹ In reaction to electric stimuli he used electrodes whose diameters were 1 mm. and 10 mm., respectively. Though no marked differences were obtained the larger areas gave, on the whole, shorter reactions.

On the other hand, there have been frequent observations of the effect of the size of the stimulus on the intensity of the sensation. Ole Bull,² Donders,³ Fick,⁴ and Guillery,⁵ in their studies on sight and the color sense, all found that the smaller the size of the retinal image the greater must be the intensity of illumination in order that the object may be perceived. The sensation of color was found to be influenced in a similar way by the size of the colored surface. Förster⁶ expressed the relation between size of stimulus and intensity of sensation as follows: "Brightness and the visual angle are the two factors which determine the vividness (Schärfe) of our visual sensations; the smaller the one, the greater must be the other one if the stimulus is to be perceived—they supplement each other."

Riccò⁷ stated the relation in mathematical terms as follows: The product of the area of the retinal image and its intensity, or the product of the visual angle and the square root of the intensity is a constant as long as the visual image does not exceed the limits of the fovea. The constant in these and similar experiments was the threshold.

Aubert⁸ confirmed Förster's statement and expressed the relation thus: The visibility of an object depends on three factors: (1) the absolute brightness, (2) the relative brightness or contrast, and (3) the visual angle or size of the retinal image.

¹ *Op. cit.*, p. 409.

² *Gräfe's Arch.* 27.

³ *Arch. f. Ophthalmologie*, 33.

⁴ *Pflüg. Arch.*, 43, 1888.

⁵ *Arch. f. Augenheilkunde.*, 31.

⁶ *Ueber Hemeralopie u. d. Anwendung eines Photometers im Gebiete d. Ophthalmologie*, Breslau, 1857.

⁷ *Ann. d'Ottamologia*, 3, 3.

⁸ *Physiologie d. Netzhaut.*, Breslau, 1865.

Piper¹ experimented with stimuli whose retinal images lay entirely outside the limits of the fovea. Using the threshold as measure of sensitivity, he found that for the dark adapted eye the stimulus value of an object increases as the square root of the area of the retinal image, or that the product of the intensity by the square root of the area is a constant at the threshold. Combining, then, the results of Riccò and Piper, the relation between size and intensity becomes (1) in the fovea, intensity $\times$ area = const.; (2) outside the fovea, intensity $\times$ the square root of area = const. Piper, however, thinks that Riccò's results need confirmation.

TABLE IX

Subject R

2000 reactions

Ser.	48		24		12		6		3	
	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.
I.	171.2	8.7	175.5	10.2	184.8	15.7	180.7	12.4	186.2	13.2
II.	177.6	11.7	176.1	9.9	178.6	10.2	182.2	10.7	193.4	9.6
III.	180.6	11.8	164.6	7.5	174.5	13.0	189.3	11.2	192.8	10.7
IV.	152.6	8.5	174.6	11.2	168.7	8.5	170.8	10.9	186.6	9.6
V.	158.5	13.5	181.7	7.2	174.6	7.1	177.2	8.8	182.7	8.9
VI.	184.4	7.7	189.1	8.2	186.4	7.2	189.8	8.1	193.4	7.9
VII.	169.1	10.5	167.8	9.2	163.3	6.8	164.6	10.8	171.4	7.2
VIII.	180.4	11.8	179.4	10.2	180.8	3.7	178.8	7.8	193.5	8.8
IX.	190.0	10.1	188.8	6.6	189.5	7.2	190.5	6.2	197.3	5.6
X.	170.8	10.7	192.2	11.2	195.0	10.6	196.5	11.6	205.5	11.6
XI.	190.3	11.4	184.5	5.9	189.2	9.2	194.2	9.2	202.8	11.2
XII.	194.6	9.9	197.0	10.2	199.6	8.0	202.7	10.7	207.8	11.2
XIII.	178.2	11.0	184.0	8.5	194.1	9.4	201.2	8.6	208.1	9.5
XIV.	184.3	10.6	178.0	12.2	194.6	9.4	192.2	12.6	191.2	12.5
XV.	188.0	7.7	190.2	8.4	178.6	10.3	198.5	10.7	200.7	12.9
XVI.	194.2	11.1	193.1	9.6	194.1	12.8	203.0	13.0	199.7	11.4
Av.	179.0	10.4	181.9	9.1	184.2	9.3	188.3	10.2	194.6	10.1
P.E.	.44		.38		.39		.43		.43	

So far only the effect of size on the threshold intensity has been shown. How it affects greater intensities must be discovered by other methods. If the relation between the intensity of the stimulus and the reaction-time is similar to that between intensity of stimulus and sensation, as the results already presented would indicate, the effect of size on supraliminal intensities may be measured by its effect on the time of reaction.

The experiments on the effect of size on the time of reaction were made at the same time with those on intensity in Tables I. and II.

¹ *Ztschr. f. Psychol.*, 32, 98, 1903.

Five sizes were used: 48, 24, 12, 6 and 3 mm. sq., respectively. The largest of these would just about cover the fovea at the distance used. It was found in preliminary experiments that further increase in the area of the stimulus had hardly any effect on the time of reaction. Piper's observation that the intensity depended on the actual area and not merely on the diameter was found to hold also for reaction-time. The results are given in Tables IX. and X. Each figure in the body of the tables is the average of 25 reactions. There seems to be a marked difference between the subjects. In the case of R.

TABLE X
Subject W 2000 reactions

Ser.	48		24		12		6		3	
	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.
I.	155.3	14.0	159.9	16.8	156.0	6.4	157.6	9.8	158.6	8.0
II.	155.5	5.3	159.6	7.5	162.7	10.3	164.1	8.2	167.1	9.5
III.	162.4	8.8	164.3	9.2	158.8	6.1	175.7	7.5	166.8	11.1
IV.	160.6	6.1	160.9	8.0	166.0	5.0	171.0	7.7	174.0	6.6
V.	163.5	8.2	191.0	11.2	178.7	5.7	172.9	5.2	189.6	9.0
VI.	162.3	5.7	167.4	7.8	158.6	5.2	159.4	5.5	167.5	5.3
VII.	164.2	11.9	166.0	7.6	153.6	7.2	160.2	4.3	169.2	5.9
VIII.	158.6	9.1	164.3	8.6	157.5	4.3	160.7	6.3	172.3	6.7
IX.	164.0	9.2	169.0	8.4	158.5	4.2	168.4	5.0	176.0	6.3
X.	175.8	9.8	176.2	11.1	175.5	9.6	180.0	10.3	188.0	9.6
XI.	177.3	6.5	171.0	7.5	176.9	8.8	173.3	9.5	180.9	8.0
XII.	178.3	10.2	172.4	7.5	179.8	7.8	180.8	10.2	180.8	9.3
XIII.	177.8	12.1	174.1	9.1	182.6	12.8	180.1	11.2	191.0	12.5
XIV.	197.7	11.0	197.6	9.7	194.4	8.5	184.5	7.8	180.2	8.4
XV.	194.8	12.5	176.1	8.3	176.0	9.7	177.1	10.0	173.1	8.9
XVI.	205.0	11.4	200.9	15.5	185.9	10.3	180.8	8.7	179.2	7.2
Av.	172.1	9.5	173.2	9.6	170.4	7.6	171.7	8.0	175.9	8.3
P.E.	.40		.41		.32		.34		.35	

the increase is fairly regular from the start, but in the case of W. there is a slight decrease at first. This difference may perhaps best be expressed by saying that the point beyond which increase of size has no further effect on the time of reaction is lower in subject W. than in subject R. The cause of it may lie in differences in the retinas of the two subjects, since in another research carried on in the same laboratory, W. was found to have a smaller field of distinct vision than R.

For comparison, the results on two other subjects, H. and F., are given in Tables XI. and XII. The averages on subject H. are obtained from 100 reactions, those on subject F. from 225.

TABLE XI

Subject H

500 reactions

Ser.	48		24		12		6		3	
	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.
I.	169.7	13.1	174.3	9.7	180.3	8.1	182.5	11.0	193.1	10.3
II.	184.5	8.7	187.8	12.4	188.0	9.6	191.7	6.0	194.5	10.3
Av.	177.1	10.9	181.1	11.1	184.2	8.8	187.1	8.5	193.7	10.3
P.E.	.92		.93		.74		.71		.86	

TABLE XII

Subject F

1125 reactions

Ser.	48		24		12		6		3	
	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.
I.	161.5	7.0	166.7	5.9	166.2	4.1	176.3	8.5	179.0	8.3
II.	169.4	8.0	168.5	6.4	165.4	8.2	173.8	8.9	176.8	9.3
III.	162.4	9.1	163.6	7.7	168.5	7.9	174.0	11.2	183.0	7.0
IV.	160.0	8.5	150.8	7.7	162.6	9.6	166.4	9.4	173.7	9.4
V.	156.0	7.4	156.0	7.2	162.9	6.9	154.6	9.2	164.3	8.0
Av.	162.5	8.0	161.7	6.9	165.1	7.4	169.0	9.5	175.4	8.4
P.E.	.47		.53		.41		.39		.45	

It will be noticed that the limit of decrease for F. is reached at 24 mm. sq., just as it was for W. at 12 mm. sq. With these exceptions the results agree fairly well.

As in the case of intensities, additional experiments have been made on still smaller stimuli in an attempt to reach the threshold. The decrease of the size of the stimulus was in these experiments accomplished by placing the subject at different distances from the apparatus. This was found to be necessary, as a further decrease of the aperture in the screen would also reduce the intensity of the stimulus. In the previous experiments the distance of the subject's eyes was, with slight variations, 35 cm. The distances chosen in these experiments were, therefore, 35, 70, 140, 280, and 560 cm., respectively. Since the size of the retinal image varies inversely as the square of the distance this arrangement gave a decrease of the same nature as the one before. The smallest stimulus was very close to the threshold; in fact it sometimes happened that it was below it, so that no experiments could be taken on that day. The results are given in Tables XIII. and XIV. The averages for subject R. represent 200 reactions, for subject W., 80.

TABLE XIII

Subject R

1000 reactions

Ser.	3		$1\frac{1}{2}$		$\frac{3}{4}$		$\frac{3}{8}$		$\frac{3}{16}$	
	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.
I.	196.1	6.5	198.5	11.9	216.6	8.8	238.3	10.8	252.0	13.4
II.	203.3	6.1	224.2	10.9	214.4	8.1	216.9	10.5	250.0	9.6
III.	197.3	7.5	200.2	8.6	209.7	9.9	208.9	10.8	222.9	9.2
IV.	207.1	6.7	206.3	9.8	209.9	8.1	229.1	13.5	238.9	10.4
V.	198.1	8.0	205.3	8.6	212.6	11.2	227.4	9.9	255.1	10.5
Av.	200.5	7.0	206.9	10.0	212.6	9.2	225.1	11.1	243.8	10.6
P.E.	.42		.63		.58		.67		.64	

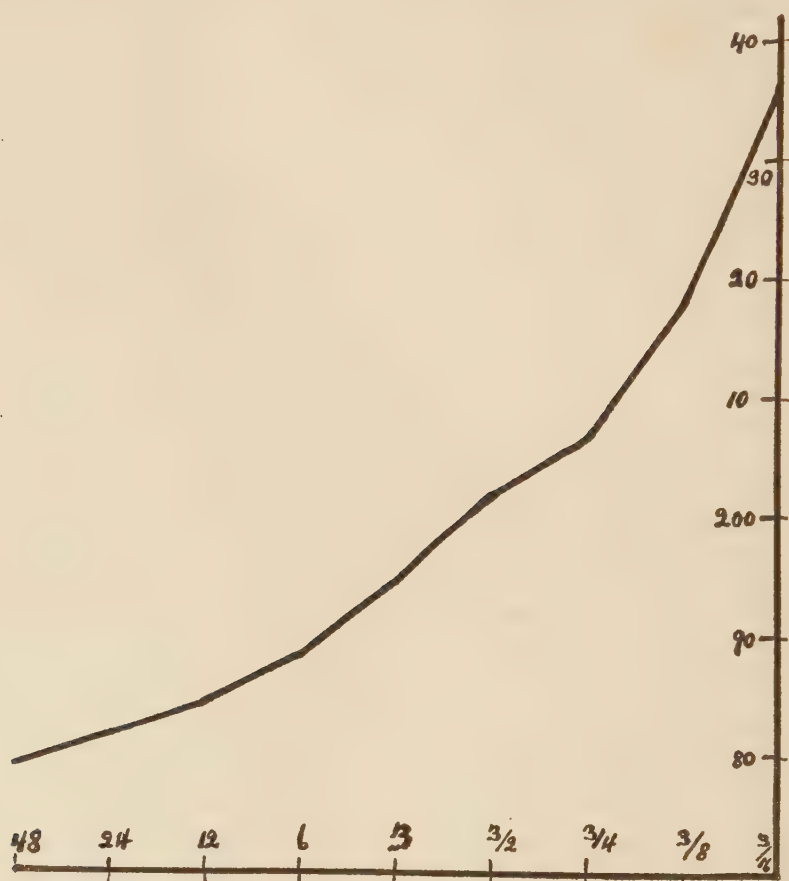


Fig. III.—Increase in the reaction-time with decrease in the area of the stimulus. Subject R.

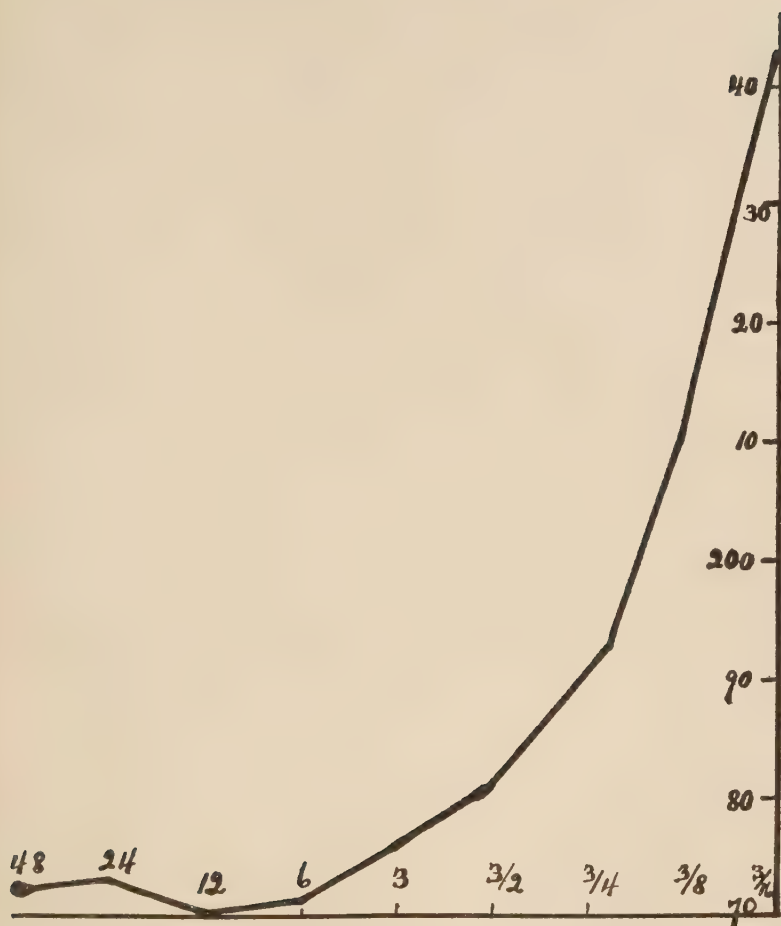


Fig. IV.—Increase in the reaction-time with decrease in the area of the stimulus. Subject W.

TABLE XIV
Subject W 400 reactions

Ser.	3		$1\frac{1}{2}$		$\frac{3}{4}$		$\frac{3}{8}$		$\frac{3}{16}$	
	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.
I.	197.3	9.8	205.3	13.7	214.2	14.0	238.4	13.2	261.2	19.4
II.	190.8	10.1	192.5	21.4	208.3	13.6	219.1	11.9	259.1	21.0
Av.	194.0	9.9	198.9	17.5	211.2	13.8	228.7	12.5	260.1	20.2
P.E.	1.19		2.11		1.82		1.51		2.45	

These results show that the time of reaction increases with decreasing size of the stimulus. Over a limited range this increase is made

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by approximately equal arithmetical increments as the size of the stimulus decreases geometrically, but as the threshold is approached the increase becomes more rapid. To show this more clearly, a table of the increments in the time of reaction, together with the P.E.'s, are given below. The result is shown graphically in Figures III. and IV.

TABLE XV

Incr.	4.0	3.1	2.9	4.6				
H.								
P.E.	.93	.84	.73	.79				
Incr.	— .8	3.4	3.9	6.4				
F.								
P.E.	.49	.47	.40	.42				
Incr.	2.9	2.3	4.1	6.3	6.4	5.7	12.5	18.7
R.								
P.E.	.41	.39	.41	.43	.53	.61	.61	.65
Incr.	1.1	— 2.8	1.3	4.2	4.9	12.3	17.5	31.4
W.								
P.E.	.41	.37	.33	.35	1.65	1.97	1.67	1.98

V. THE EFFECT OF VARIATION OF DURATION ON THE TIME OF REACTION

No account seems to have been taken in work on reaction-time of the influence of the duration of the stimulus. Generally, the stimulus has been allowed to act until the reaction has been made. On the other hand, the relation between the duration of the stimulus and the intensity of the sensation has been extensively investigated. The first one to call attention to the subject was Talbot.¹ His experiment consisted in revolving a point of light at such a speed that the appearance of a luminous ring was produced, and his conclusions he stated as follows: "Since, then, these two things—the intensity of the light and the body's remaining in any given part of the circle—are each inversely proportional to the circumference of the circle it describes, it follows that they must be directly proportional to each other." This principle, known as Talbot's Law, has later been verified by Bloch,² Carpentier³ and Fick.⁴ Swan⁵ arrived independently at the conclusion that when a light acts on the retina for a short period of time the brightness of the sensation is exactly proportional to the time during which it acts. Exner⁶ found that the curve representing the rise of a sensation to its maximum was a straight line, which indicates that below that point the intensity of the sensation is exactly proportional to the duration of the stimulus. McDougall,⁷ after an extensive study of the same problem, arrived at the following conclusions: (1) The action-time of light varies inversely with its intensity from 0.2 to 0.03 sec.; (2) when the duration of the action of light is less than its action-time, the intensity of the sensation is directly proportional to the duration of the stimulus; (3) the action-time of the minimum perceptible light is about 0.2 sec. Büchner⁸ obtained practically the same results except that the rise of the sensation showed slight oscillations, similar to those that follow upon a momentary excitation of the retina.

Since, thus, the intensity of the sensation is directly proportional to the duration of the stimulus, it would naturally be expected that the two would affect the time of reaction in the same way. The stimuli in these experiments were, therefore, chosen in such a manner that they would produce approximately the same sensations as

¹ *Philos. Mag.*, Ser. 3, 5, 327.

² *C. R. de la Société de Biologie*, 1885, Ser. 18, p. 495.

³ *Ibid.*, 1887, 2, 5.

⁴ *Hermann's Handb. d. Physiol.*, III., 1, 216.

⁵ *Trans. Roy. Soc. of Edinburgh*, 1849.

⁶ *Sitzber. d. Wiener Akad.*, 1868, Abth. II., 58, 601.

⁷ *Brit. J. of Psychol.*, 1, 151, 1904.

⁸ *Psychol. Stud.*, Bd. I., hft. 1, 1906.

those in the intensity series. They consisted of five strips of paper, 48, 24, 12, 6 and 3 mm. wide, respectively. As the speed was 1 mm. per σ , the stimuli were exposed for periods of 48, 24, 12, 6 and 3 σ , respectively. The durations were all well within the limits of the action-time. It would have been desirable to decrease the duration of the stimulus still further until the threshold was reached, but the mechanical difficulties have so far proved insuperable. By comparing it with intensity, however, it has been estimated that the threshold of duration for this particular white would lie somewhere between $3/64$ and $3/128\sigma$. The intensity was 100 and the size of the aperture through which the stimulus was seen was 3 mm. sq., both being constant throughout. The reactions were taken in the same series as those on intensity in Tables III. and VI. The results are given in Tables XVI. and XVII., each of which contains 2000 reactions, 25 to each figure in the body of the tables and 400 for each average.

TABLE XVI

Subject R

2000 reactions

Ser.	48		24		12		6		3	
	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.
I.	185.5	10.3	190.5	7.4	188.8	8.7	193.8	11.6	204.0	10.7
II.	190.1	11.4	195.8	10.0	193.3	8.9	195.6	8.8	200.1	14.7
III.	194.6	12.0	199.2	13.6	207.4	11.9	203.7	11.3	204.2	16.4
IV.	187.8	10.3	185.5	13.9	199.1	13.1	194.0	10.5	187.4	11.8
V.	187.6	12.2	199.0	11.6	205.6	11.6	202.0	10.0	205.6	14.7
VI.	179.4	12.2	174.6	11.8	176.7	13.4	187.8	9.2	190.7	9.1
VII.	171.8	12.1	175.4	16.7	178.4	13.2	176.1	13.4	188.7	13.6
VIII.	175.0	15.7	180.6	12.7	180.9	15.5	188.1	13.0	179.8	11.2
IX.	188.2	13.6	189.3	10.7	190.2	12.5	206.8	10.5	187.8	13.8
X.	204.2	8.2	199.7	10.8	205.3	9.1	201.7	12.7	218.6	11.4
XI.	197.2	10.1	194.0	10.1	204.1	7.4	207.1	7.0	206.8	12.6
XII.	206.0	13.4	210.2	11.0	207.1	11.1	206.1	14.6	206.4	11.8
XIII.	205.5	9.4	209.9	11.7	189.9	10.8	209.2	13.0	214.7	12.0
XIV.	196.9	8.2	195.2	9.5	209.7	9.4	204.6	9.3	209.7	9.8
XV.	192.1	10.4	197.2	9.9	196.4	9.3	193.4	9.9	199.0	9.6
XVI.	199.2	11.2	207.8	9.2	208.5	8.5	208.2	11.4	207.8	9.9
Av.	191.1	11.3	193.5	11.3	196.4	10.9	198.7	11.0	200.6	12.1
P.E.	.48		.48		.46		.46		.51	

It is thus seen that the time of reaction increases with decreasing duration of the stimulus. If the irregularities be disregarded as probably due to disturbing factors, the further conclusion may be drawn that the time of reaction tends to increase arithmetically as

the duration of the stimulus decreases geometrically. The increments and their P.E.'s are given in Table XVIII., and the results shown graphically in Figures V. and VI.:

TABLE XVII
Subject W 2000 reactions

Ser.	48		24		12		6		3	
	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.
I.	165.3	7.6	165.4	6.3	165.3	7.0	166.6	9.0	166.7	5.3
II.	168.3	7.0	166.2	8.2	164.6	7.9	170.6	8.6	171.9	10.8
III.	170.6	6.7	170.9	7.0	170.6	5.2	166.2	5.8	168.4	6.2
IV.	182.7	9.8	180.2	9.1	175.6	9.6	181.0	6.6	182.4	10.2
V.	176.9	4.6	176.7	5.4	179.3	6.0	179.4	7.6	181.7	5.5
VI.	171.0	6.5	162.7	4.8	166.8	6.6	166.8	10.5	168.6	10.3
VII.	158.8	7.4	158.8	11.3	169.3	7.9	164.5	7.5	169.4	5.5
VIII.	154.2	11.4	148.8	8.8	151.9	10.5	161.4	6.4	159.5	8.2
IX.	164.4	9.7	176.2	12.4	173.2	8.9	183.0	11.5	185.8	8.6
X.	173.5	8.7	180.9	6.9	181.9	7.1	184.1	7.6	179.0	7.9
XI.	173.6	5.3	164.9	9.1	177.9	6.5	170.7	6.4	172.0	7.1
XII.	181.2	9.2	186.2	10.7	182.0	11.0	188.6	10.0	197.5	11.0
XIII.	181.2	6.4	201.8	10.4	199.4	11.6	198.3	13.7	200.4	12.5
XIV.	180.4	8.4	183.4	8.7	189.5	9.9	200.8	14.7	204.6	13.7
XV.	181.4	8.1	195.9	8.9	195.7	13.3	186.8	12.0	189.0	7.6
XVI.	190.1	10.0	190.7	11.9	195.4	6.3	197.8	10.4	195.3	10.6
Av.	173.4	7.9	175.2	8.7	177.4	8.5	179.2	9.3	180.7	8.8
P.E.	.33		.37		.36		.39		.37	

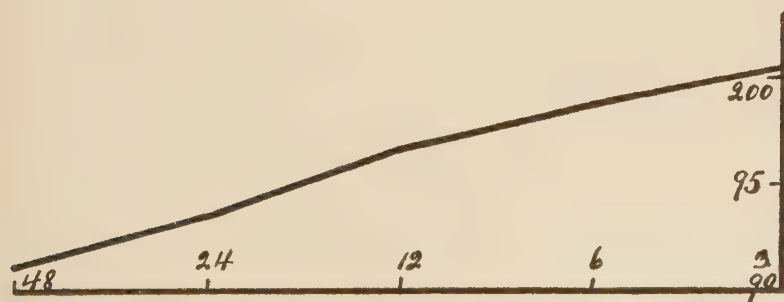


Fig. V.—Increase in the reaction-time with decrease in the duration of the stimulus. Subject R.

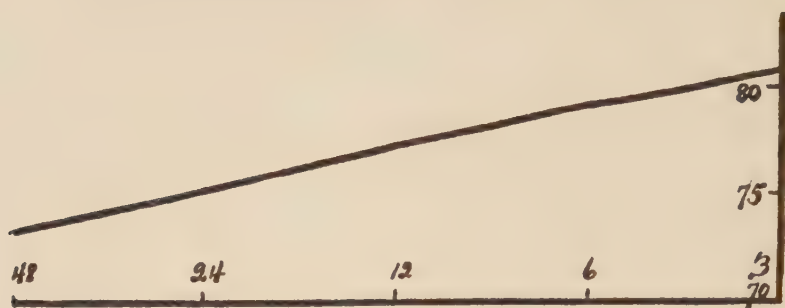


Fig. VI.—Increase in the reaction-time with decrease in the duration of the stimulus. Subject W.

TABLE XVIII

R.	Incr.		2.9	2.3	1.9
	P. E	.48	.47	.46	.49
W.	Incr.	1.8	2.2	1.8	1.5
	P.E.	.35	.37	.38	.38

VI. COMPARISON BETWEEN THE STIMULUS VALUES FOR REACTION OF INTENSITY, SIZE AND DURATION

Having thus determined the relation between the time of reaction and the several factors of the stimulus, the problem remains to show how these are related to one another. To make possible a direct comparison, the experiments were planned in such a way that one stimulus was to be common to the three series on intensity, size and duration. The intensity of this stimulus was 100, its size 48 mm. sq., and its duration 48σ. Starting with this stimulus, the intensity was to be decreased in one series, the size of the next, and duration in the third, the other two factors remaining constant in each series. Since it was expected that a decrease in duration would have approximately the same effect as a decrease in intensity, these two factors were decreased by equal amounts by taking each stimulus one-half of the preceding. But as the effect of variation in size was found, from preliminary experiments, to be considerably weaker, the size was decreased by taking each stimulus one-fourth of the preceding. The stimuli chosen were approximately in the middle of the scale of size and duration as well as intensity. If this plan could have been carried out the influence of the several factors could have compared with each other directly, but on account of mechanical difficulties, the duration of the largest stimulus could not be decreased to 3σ. In all the experiments on duration, therefore, the smallest size, 3 mm. sq., had to be used, but the intensity was, as in the experiment on size, 100. It is conceivable that the smaller size in these experiments might not only increase the time of reaction but might also affect the influence of the duration of the stimulus. To test this and also calculate its amount if found present, with every series on duration, a series on intensity was taken, in which also the size of the stimulus was 3 mm. sq. If the variation in size does affect the influence of the intensity the result from the two series should be different. Below are given the results of the two series in the form of increments in the time of reaction, *l* denoting the larger and *s* the smaller stimulus.

TABLE XIX

<i>l.</i>	4.2 3.0 2.4 3.0
R. <i>s.</i>	3.1 2.9 4.4 6.5 3.4 5.1 4.8 5.9
<i>l.</i>	3.9 3.1 2.5 2.6
W. <i>s.</i>	2.5 4.6 2.9 1.6 3.1 5.6 —1.2 3.0

As no marked differences appear, it may be concluded that within these limits the decrease in size has simply increased the time of reaction without affecting the influence of the intensity factor. It may therefore be safely assumed that the influence of duration also remains unaffected by the decrease in size, and that all three factors are independent variables. The results from the experiments on the influence of duration are therefore directly comparable with those on the other two, just as if the size had been 48 mm. sq. instead of 3 mm. sq.

To express the relative effect of variation of any factor of the magnitude of the stimulus the term stimulus value has been used. Piper uses it in this sense when investigating the relation between the effect of variation of intensity and that of size on the resulting sensation. The relative stimulus value of size and intensity, when applied to the time of reaction, is the relative effect of variation of these two factors on the time of reaction. These are given in Table XX. in terms of increments in the time of reaction. The range of decrease for intensity is from 1 to 1/16 and for size from 1 to 1/256. In order to bring the intensity down to $6\frac{3}{4}$, or approximately 1/16 of 100, the increments 3.4 and 3.1, respectively, are added.¹

TABLE XX

R.	Int.	4.2 3.0 2.4 3.0 (+3.4), Total range = 16.0				
	Size	2.9 2.3 4.1 6.3, " " = 15.6				
W.	Int.	3.9 3.1 2.5 2.6 (+3.1), " " = 15.2				
	Size	1.1 —2.8 1.3 4.2, Range of last half = 5.5				

If the first half of the size series on W. is excluded for reasons already explained, the result shows that the effect of decreasing the intensity in the ratio of 1/2 is approximately the same as the effect of decreasing the size in the ratio of 1/4. The relative stimulus value of these two factors may, therefore, be expressed by the formula

$$I \times \sqrt{S} = \text{const.}$$

This is the same relation that Piper² found to hold between these factors with respect to their effect on sensation.

The meaning of the formula, as used by Piper, is that, provided the intensity and area of the stimulus are varied so as to leave the product of the intensity by the square root of the area always the same, the sensation produced remains constant, at least at the thresh-

¹ See above, p. 17.

² *Ztsch. f. Psychol.*, 32, 107, 1903.

old. Similarly, as used here, the formula means that provided the product of intensity by the square root of area is kept constant, the reaction-time will remain constant.

The relative stimulus value of intensity and duration is shown in Table XXI. The range is the same for both factors, namely from 1 to 1/16.

TABLE XXI

R.	Int.	3.1 2.9 4.4 6.5 (+3.4), Total range = 20.3									
	Dur.	2.4 2.9 2.3 1.9 " " = 9.5									
W.	Int.	2.5 4.6 2.9 1.6 (+3.1), " " = 14.7									
	Dur.	1.8 2.2 1.8 1.5 " " = 7.3									

The result shows that the increment in the time of reaction produced by a decrease of duration is only one-half of that produced by the same decrease in intensity, and, therefore, in order to obtain the same effect, the duration has to be decreased in the ratio of 1/4 as in the case of size. Consequently, the relation between them may be expressed by the formula

$$I \times \sqrt{T} = \text{const.}$$

where T is the duration of the stimulus.

This result is rather surprising in view of the fact that the intensity of a sensation is directly proportional to the duration of the stimulus. Theoretically, the sensation produced by intensity 100 exposed for 12σ should be the same as that produced by intensity 25 exposed for 48σ , and observation proved this to be the case, but the reaction to it is shorter. Similarly, the sensation produced by intensity 100 exposed for 3σ , is the same as that produced by $6\frac{1}{2}$, exposed for 48σ , but the time of reaction to the former is 10.5σ shorter for R. and 7.4σ shorter for W. Since the sensation is the same in both cases but the time of reaction differs, it follows that the latter cannot be dependent on the former but is produced directly by the stimulus. From frequent observation and introspection it became evident that the reaction movements in these experiments were reflexes with which consciousness had little to do except to prepare the subject for the stimulus. It is generally held that in reflex and habitual reactions there are separate nervous processes for sensation and movement, and it is thought that these experiments furnish additional evidence in favor of this view.

The relation between the stimulus value of size and duration may be deduced from their relation to the stimulus value of intensity. Since they stand in the same relation to intensity they should be equal.

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The actual result is given in Table XXII., where the range of size is from 1 to 1/256, and of duration from 1 to 1/16.

TABLE XXII

	Size	2.9	2.3	4.1	6.3,	Total range = 15.6		
R.								
	Dur.	2.4	2.9	2.3	1.9,	"	"	= 9.5
	Size	1.1	—2.8	1.3	4.2,	Last half = 5.5		
W.								
	Dur.	1.8	2.2	1.8	1.5,	Total range = 7.3		

Bearing in mind that the range of size is twice that of duration, it is thus seen that the stimulus value of these two factors is nearly, but not quite, the same, that of duration being the greater. The difference, however, is small enough to be due to occasional errors. If this be the case, the formula expressing the relation between them is

$$S \times T = \text{const.}$$

A suggestion may be made as to the bearing of these results on the interpretation of the so-called Weber's Law. If the logarithmic relation is obtained in nervous processes, which are independent of sensation, as the reaction has been shown to be under certain conditions, it is probable that, when a similar relation is found to exist between stimulus and sensation, this is due not to the mystical nature of the mental processes but to the physiological processes involved.

VII. EXPERIMENTS ON SOUND

There has been some disagreement as to the influence of intensity on the time of reaction to sound. While Wundt, and also Berger and Cattell, found that the time of reaction increased with decreasing intensity, Götz Martius¹ later reported some experiments in which he found the intensity of the sound to have no influence whatever on the time of reaction. He further goes on to explain that, whenever lower intensities do affect the reaction-time, this is due to the fact that the attention of the subject is not adapted to the stimulus. This, he thinks, applies not only to sound but to all other stimuli. Martius' results, however, are open to criticism. The range of his intensities was small, and no actual measurement made of them. Only 20 reactions were taken to each stimulus, and since some of these were discarded as not being true reactions, each average is the result of from 11 to 20 reactions. From such meager data no safe conclusions can be drawn.

Slattery² also reports some experiments on reaction to sounds of different pitch and intensity, in which he claims to find no effect of intensity on the time of reaction, and offers his results as further proof of the correctness of Martius' conclusions. His results, however, are also obtained from a small number of experiments to each stimulus. The times, moreover, are rather long for reactions to sound, 282-299 σ and 249-218 σ , respectively, for the two subjects, and the mean variations are extremely large, 61-72 σ and 57-68 σ , respectively. Finally, the results differ for the two subjects, increasing with decreasing intensity for the more practiced subject, and the reverse for the other. No valid conclusion as to the relation between intensity of stimulus and time of reaction can be drawn from these results, but they serve to show the desirability of further investigation of the subject. For this reason, as well as for the purpose of comparing results from different sense departments, a set of experiments on sound were made. It was clearly understood, however, that none but the most general relation between stimulus and time of reaction could be established in this field, since a reliable method of measuring the intensity of sound is still lacking.

The apparatus used in these experiments was a slightly modified form of an apparatus constructed by Ernest Kempton Adams for measuring the sensitiveness to differences in the intensity of sound. It consisted of a cylindrical block of soft iron resting on a low wooden stand and carrying two uprights, 1.3 m. long. To one of these a magnet was fastened in such a manner that it could be adjusted at differ-

¹ *Phil. Stud.*, 7, 469.

² *Stud. fr. Yale Psych. Lab.*, 1892-1893, p. 71.

ent distances from the block. The magnet was used to drop a steel ball of perfectly spherical form and of uniform composition as far as could be determined. The diameter of the ball was 13 mm. and its weight 8.37 g. Direct contact with the magnet was prevented by covering the latter with a piece of chamois skin. An immediate drop of the ball was thus obtained as soon as the current through the magnet was broken. A hard rubber tube fitted to the ball, 1 cm. long, was glued to the end of the magnet and this served to keep it in place and guide it in the first part of its fall. The top of the block was inclined at an angle of 45° , so that the ball, on striking it, bounced off and was received noiselessly by a basket. In order to reduce the sound as far as possible, the block was covered by five thicknesses of cloth weighing 10.6 mg. per sq. cm. The apparatus was placed at one end of an inside dark-room of the laboratory, where the noise from the street could be but faintly heard. At the other end of the room, 6.6 m. away, the subject was seated with his right ear toward the source of sound, but in such a manner that he could not see the ball as it fell. The recorder, the chronoscope and the apparatus for operating the magnet, were in another room, separated from the first by two doors and an intervening room. One of the doors was left open so that the sound of the chronoscope, which served as a preparatory signal for the subject, could just barely be heard. The apparatus for the making of the circuit and releasing the ball consisted of a Scripture multiple key, through which passed both the current from the gravity cells operating the chronoscope and the current from the University lighting plant, which operated the magnet. In the circuit of the latter a lamp battery was inserted in order to obtain the required resistance. By means of this key the ball was released simultaneously with the closing of the chronoscope circuit. The time of demagnetization, though not measured, was undoubtedly small, so that the ball may be regarded as beginning its fall at the instant the current through the chronoscope was closed. The time of fall was calculated from the height and subtracted from the total time. The time required for the sound to travel from the apparatus to the observer, amounting to 20σ , was also subtracted. A third person picked up the ball and placed it in position again as soon as it fell. This permitted the series to be taken rapidly and regularly, one reaction being taken on the average every nine seconds. As the top of the block was slanting, a horizontal deviation of the ball might introduce considerable error in the results. There were, however, no air currents in the room to deflect the ball from its course. Oscillations of the rods carrying the magnet were prevented by clamping their upper ends to the wall. It is, therefore, believed that the error due to this cause is very slight. An

actual test of its extent was made by letting the ball fall on a sheet of white paper glued to the block. Every drop of the ball made a dot on the paper and a determination of the mean variation of 100 such dots would indicate the extent of the error. But this was found to be so small that an exact calculation of it was not deemed necessary; it was considerably less than 1σ . The order of presenting the stimuli was the same as in the experiments on visual stimuli. The experiments were made on two subjects, W. and B., either in the evening or at such other times as would be free from disturbing noises in the corridors and other parts of the building. Five different intensities were used, produced by letting the ball drop from successive heights of 16, 121, 324, 625 and 1024 mm., this being the greatest range permitted by the apparatus.

The results with their A.D.'s and P.E.'s are given in Tables XXIII. and XXIV., which contain each 2000 reactions, 400 for each stimulus and 80 for each figure.

TABLE XXIII

Subject W

2000 reactions

Ser.	1024		625		324		121		16	
	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.
I.	139.9	8.8	143.6	12.0	153.9	14.9	176.4	11.3	200.8	13.7
II.	126.1	9.2	130.7	9.4	130.8	9.7	141.8	9.9	190.8	17.8
III.	125.7	9.2	128.4	8.9	137.9	13.7	141.8	13.9	197.2	19.4
IV.	123.8	9.4	124.0	9.3	129.7	11.9	147.7	13.9	177.5	13.8
V.	139.2	9.1	144.7	12.8	151.6	14.6	153.3	14.2	191.7	20.6
Av.	130.9	9.1	134.3	10.5	140.8	13.0	152.2	12.6	191.6	17.1
P.E.	.38		.44		.55		.53		.72	

TABLE XXIV

Subject B

2000 reactions

Ser.	1024		625		324		121		16	
	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.
I.	168.5	14.4	178.2	13.7	180.9	13.8	209.9	19.6	261.1	24.2
II.	155.5	14.9	158.3	22.0	152.6	16.6	197.7	30.7	220.8	23.2
III.	157.4	15.2	153.2	14.4	152.6	14.7	176.6	14.9	219.5	19.8
IV.	166.1	14.3	161.4	16.2	174.5	17.6	195.6	22.2	229.5	24.3
V.	150.4	11.4	158.7	11.7	163.7	14.9	174.4	14.9	229.6	19.9
Av.	159.6	14.0	161.9	15.6	164.9	15.5	190.8	20.4	232.1	22.3
P.E.	.59		.66		.65		.86		.94	

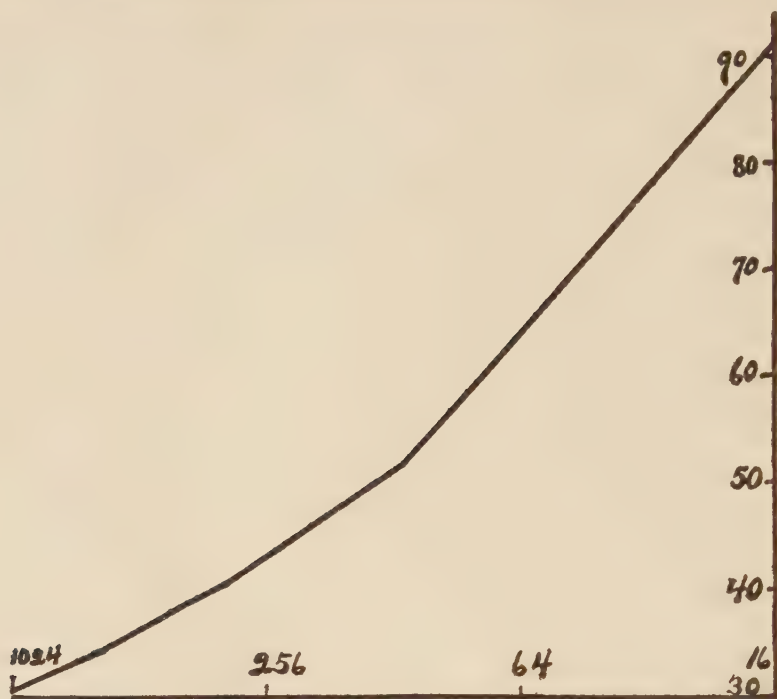


Fig. VII.—Increase in the reaction-time to sound with decrease in the intensity of the stimulus. Subject W.

The results are shown graphically in Figures VII. and VIII., where the ordinates are proportional to the time of reaction in σ and the abscissas to the logarithm of the intensity of the sound as calculated from the formula

$$I = M \times H,$$

M being the mass and H the height of fall of the steel ball.

It is evident that the time of reaction increases with decreasing intensity of sound and that this decrease cannot be due merely to the non-adjustment of attention, for the attention had ample time to become adjusted and did become adjusted to the stimulus in a series of 80 reactions to the same intensity. If the physical intensity of sound be taken proportional to the height of fall of the ball, the increase in the time of reaction is somewhat more rapid than the corresponding decrease in the logarithm of the stimulus, but as long as the relation between the height of fall and the physical intensity of sound is not definitely settled, none but a general inverse relation can be established.

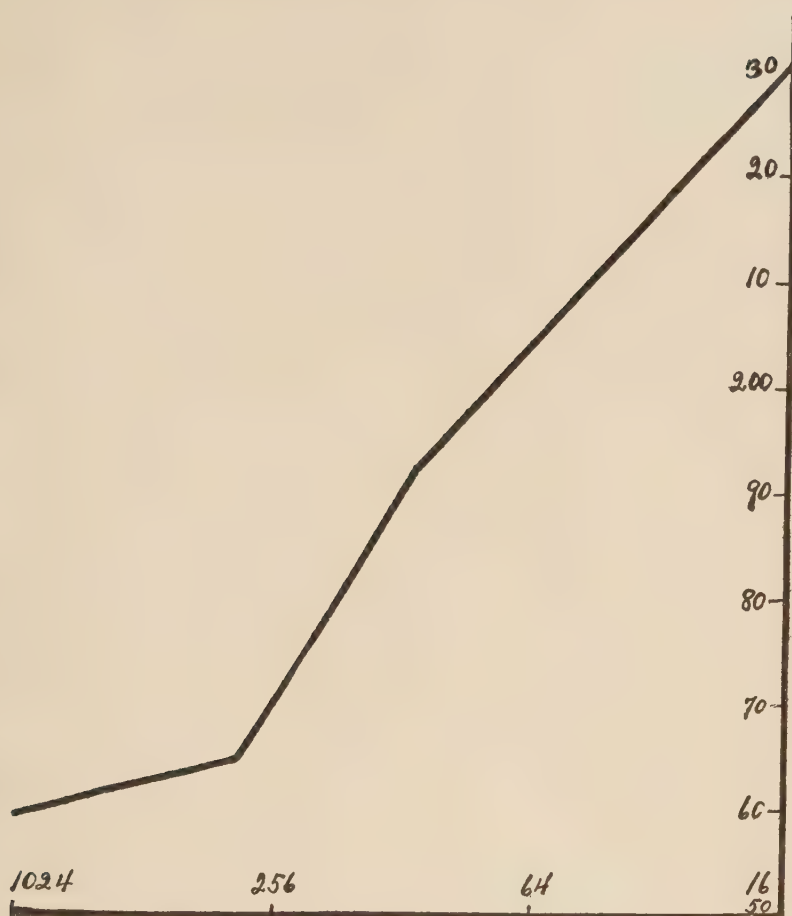


Fig. VIII.—Increase in the reaction-time to sound with decrease in the intensity of the stimulus. Subject B.

VIII. CONCLUSION

The purpose of this investigation has been to inquire into the relation between the magnitude of the stimulus and the time of reaction. This has been done for all three factors of the magnitude in the case of visual stimuli and for intensity in the case of sound. The results may now be briefly summarized.

1. A historical survey of the subject shows that the time of reaction has been found, in a general way, to vary inversely as the intensity of the stimulus, but semi-constant errors, which are apt to influence all reaction-time experiments, have so obscured the results as to make a more definite statement of the relation impossible.

2. The experiments here made, though perhaps slightly influenced by the same errors, show that in the middle of the scale the time of reaction tends to increase arithmetically as the magnitude of the stimulus decreases geometrically, and that this applies to all three factors of the magnitude.

3. The experiments on sound show that a general inverse relation exists between the intensity of stimulus and the time of reaction, but on account of the lack of a reliable measure of the physical intensity of sound a more definite relation cannot yet be established.

4. The relation of the several factors of the stimulus to each other, or their relative stimulus value, may be expressed by the formulas

$$I \times \sqrt{S} = \text{const.}; \quad I \times \sqrt{T} = \text{const.}; \quad S \times T = \text{const.}$$

The writer desires to express his great obligations to Professor Cattell, Professor Woodworth and Professor Thorndike for their kind interest and valuable suggestions, and to Dr. Henmon, Dr. Wells, Mr. Ruediger and Mr. Brown, of the Department of Psychology, for their generous assistance as subjects in these experiments.

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